Are there really more particles than anti-particles in the universe?

Hitoshi Murayama
50 Years of Antiprotons
LBNL, Oct 29, 2005

Where is anti-matter?

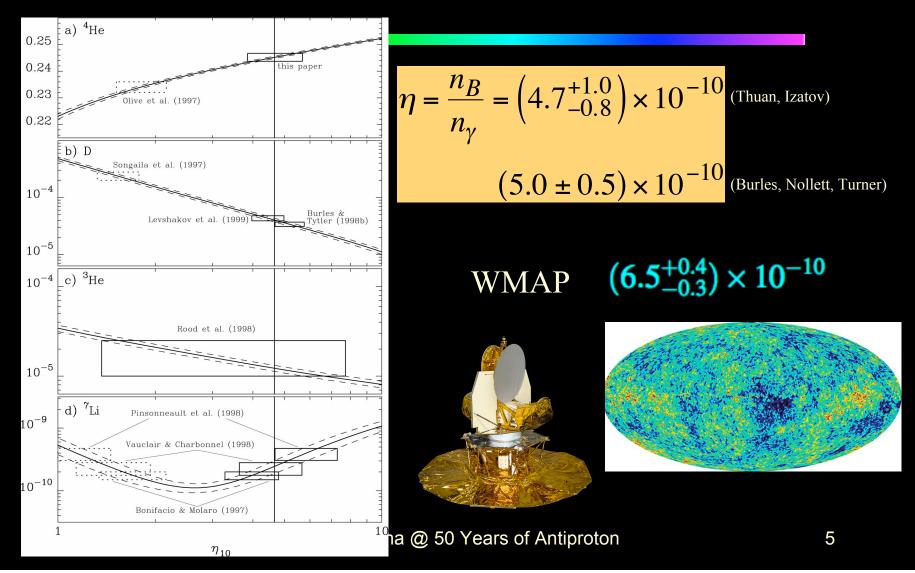
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Outline

- Introduction
- Standard Picture
- Observational limits on anti-matter in the universe
 - Anti-matter in our galaxy
 - Anti-matter in cluster
 - Anti-matter on cosmological scales
- Causality argument against anti-matter domains
- Conclusions

Standard Picture

Big-Bang Nucleosynthesis Cosmic Microwave Background



Baryon Asymmetry Early Universe

10,000,000,001 10,000,000,000

10,000,000,000

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The Great Annihilation

Baryon Asymmetry Current Universe

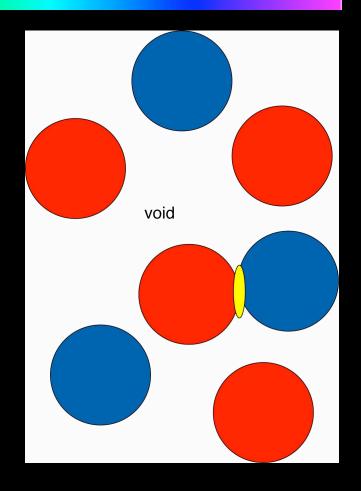
us

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The Question

- We are made of matter
- Berkeley made anti-matter
- Big Bang made presumably both matter and anti-matter, too
- Where did it go?
- Are there anti-matter domains in the universe?
- Could the universe be *baryosymmetric*?



Basic premise

- Short answer: *no!*
- Universe is not empty
 - Structured at various levels
 - interstellar medium, intracluster gas
- Anti-matter shouldn't be close to matter
 - Otherwise they annihilate
 - Produce gamma rays
 - Cosmic microwave background, diffuse gamma rays
- How did anti-matter get separated to begin with?
 - Need to violate causality

Anti-matter in Solar System

Not likely

- Landing on the moon
- Past asteroid/meteor impact
- Solar cosmic rays
- Voyager spacecraft







ama @ 50 Years of



Anti-matter in Our Galaxy

BESS

Balloon-borne Experiment with a Superconducting Spectrometer



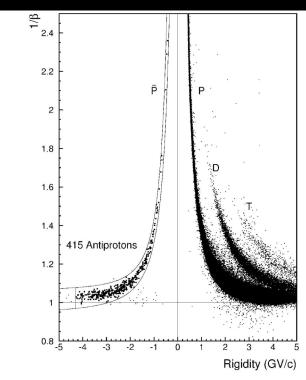


FIG. 2. The identification of \bar{p} events. The solid lines define the \bar{p} mass band used for the spectrum measurement.

Anti-protons

- There are anti-protons in cosmic rays
- $\sim 10^{-4}$ of protons
- Consistent as secondaries due to the interaction of cosmic-ray protons in the ISM (InterStellar Medium)
- Certainly not 1:1

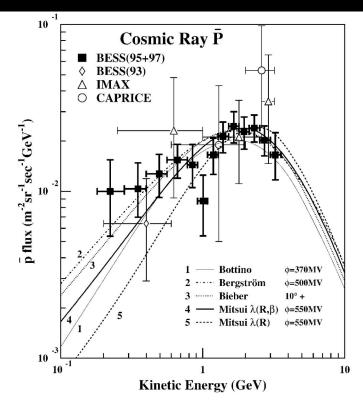


FIG. 3. BESS 1995 + 1997 (solar minimum) antiproton fluxes at the top of the atmosphere together with previous data. The error bars represent the quadratic sums of the statistical and systematic errors. The curves are recent calculations of the secondary \bar{p} spectra for the solar minimum period.

Anti-matter in Cluster

Anti-Helium

- Anti-nuclei unlikely form as secondaries
- Anti-helium product of BBN in anti-matter domains
- Extragalactic anti-matter within ~10Mpc should give ~10⁻⁶ anti-helium flux (Stecker)
- BESS 2002 excluded this level
- Not conclusive?

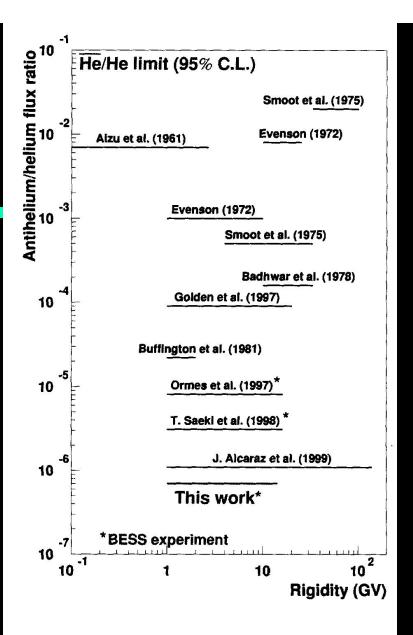
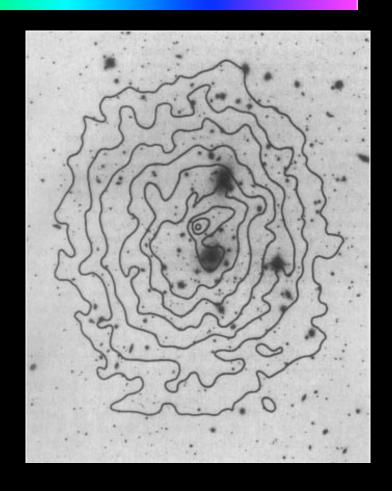


Figure 6. New upper limit of $\overline{\text{He}}/\text{He}$ obtained in this work shown with previous BESS results(BESS 1993-1995 and 1997-2000), and with other experiment results.

Galaxy Clusters

- No gamma rays from other *X*-ray emitting clusters (sure to have intracluster gas)
- No coexistence of matter and anti-matter within ~20Mpc scale
- >10¹³–10¹⁴ M_{\odot} only matter, little antimatter

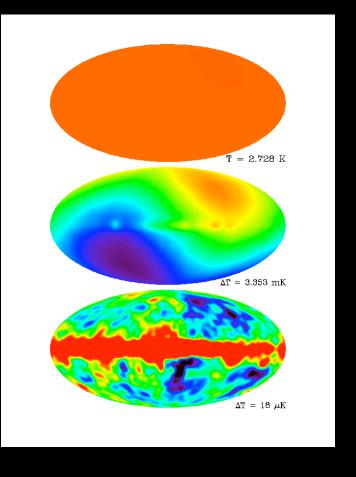


Anti-matter on Cosmological Scales

Cohen, De Rujula, Glashow (1997)

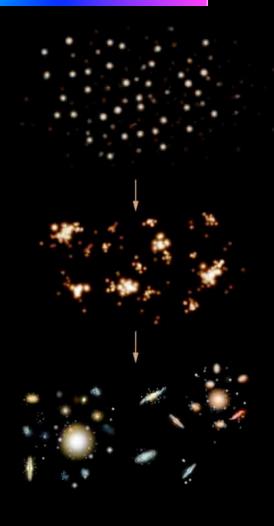
Before Recombination (z>1100)

- To avoid annihilation, need void between galaxies and anti-galaxies (or clusters)
- O(1) density fluctuations!
- unacceptably large anisotropies in CMB ~10⁻²-10⁻¹>>10⁻⁵
- Only way out: make voids very small within the resolution of CMB
 <15Mpc at the time of recombination
- However, the photon pressure moves domains closer and fills the void up to ~16Mpc



Structure Formation (z<20)

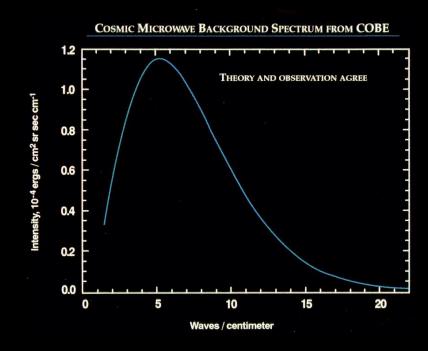
- Density fluctuation grows by gravity
- It could well form structure with both matter and anti-matter, leading to intense annihilation
- However, the annihilation leads to gamma rays and the photon pressure may stop the gravitational collapse
- Assume that the mixed structure does not form
- Conservative assumption that minimizes the annihilation gamma rays
- Do not discuss non-linear regime (e.g., z>20)



Unavoidable Annihilation

- It leaves 1100>z>20 for annihilation
- Density must be smooth, void must be filled
- Domains touch each other and annihilation takes place at the interface
- CMB distortion?
- Diffuse gamma ray background?

COBE/FIRAS



CMB distortion

- Annihilation photons
 Compton scatter,
 making the CMB
 spectrum harder
- Significant effect only on high-energy tail
- Current limits do not exclude this

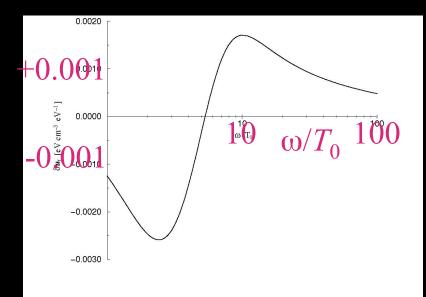


Figure 4: The CBR spectral distortion. Beyond the range shown, $\delta u_{\gamma} \propto 1/\sqrt{\omega}$, up to $\omega/T_0 \sim 10^4$.

Diffuse Gamma Ray Background

- Most of the gamma rays from π^0 are still around
- Contributing to the diffuse gamma ray background
- d_0 <1Gpc excluded

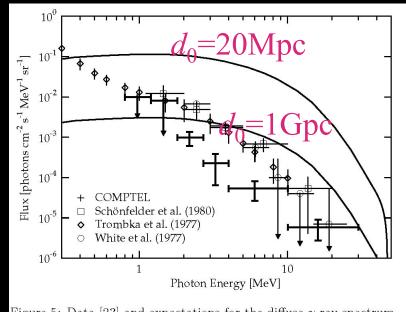


Figure 5: Data [23] and expectations for the diffuse γ -ray spectrum.

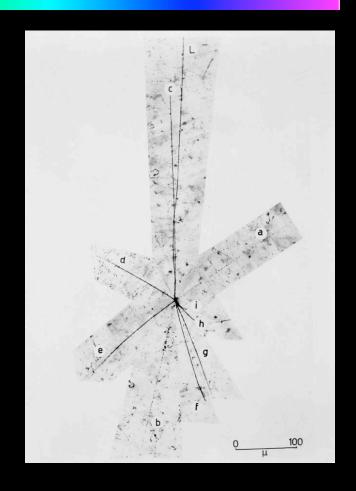
Causality

No communication

- We learned that matter and anti-matter domains (if they exist) must be separated beyond >1Gpc, basically the size of the visible universe now.
- A new force that repels matter and anti-matter?
- Distance of ~1Gpc has just come to see each other
- No causal mechanism could separate them
- Think what could have happened in earlier universe well before recombination

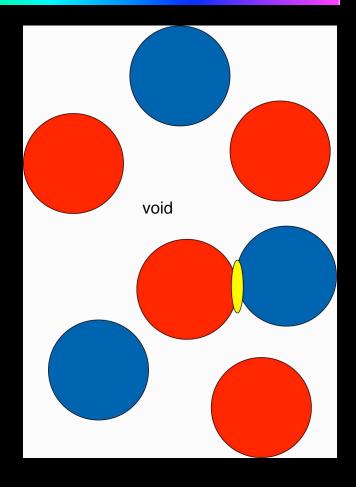
QCD phase transition

- In early universe above the QCD phase transition (*kT*>100MeV), both *q* and anti-*q* produced by gluons
- Once the $T < T_c$, they all hadronize
- Gas of baryons, antibaryons, and mesons
- Baryons and anti-baryons annihilate immediately
- End up with $n_B/n_{\gamma} \sim 10^{-20}$ everywhere in universe



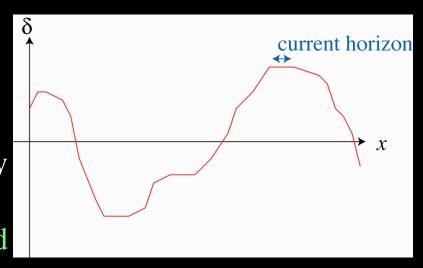
Requirement for separating domains

- Domains of matter and anti-matter must have been well separated *before* the QCD phase transition to avoid this near-total annihilation
- Horizon size back then $\sim 10^{-7} M_{\odot}$
- Need to separate $>>10^{13}M_{\odot}$
- Need acausal mechanism



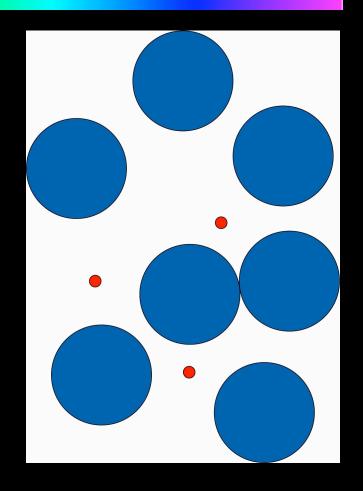
Spontaneous CP violation

- Assume a source of CP violation is determined by a VEV of a scalar field
- The field can vary from one horizon to another
- Inflation stretches it so that it is nearly constant, varies only on superhorizon scales
- The anti-matter domain could exist just beyond the current visible universe
- Not easy to do "just right"



Pockets of insurgency

- Current visible horizon is matter, little anti-matter
- Give up baryosymmetric universe
- But, small pockets of antimatter are still possible?
- antizillah (Khlopov-Rubin-Sakharov 2000)
 ~1kpc-1Mpc
- anti-lumps (Oaknin, Zhitnitsky 2003) microscopic



Conclusions

- Observations exclude baryosymmetric universe made of separated matter and anti-matter domains
- Domain size at least ~1Gpc, basically the visible universe
- Yet, anti-matter domains may exist beyond the visible horizon
- Pockets of insurgency? May still be worthwhile looking for anti-nuclei or annihilation gammas in cosmic rays